

**REUSABLE THERMAL PROTECTION SYSTEM DEVELOPMENT - A PROSPECTIVE**

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**ABSTRACT**

This paper describes the state of the art in passive reusable thermal protection system materials. Development of the Space Shuttle Orbiter, which was the first reusable space vehicle, is discussed. The thermal protection materials and design concepts and some of the shuttle development and manufacturing problems are described. Evolution of a family of rigid and flexible ceramic external insulation materials from the initial shuttle concept in the early 1970s to the present time is described. The important properties and their evolution are documented. Application of these materials to vehicles currently being developed and plans for research to meet the space programs future needs are summarized.

**INTRODUCTION**

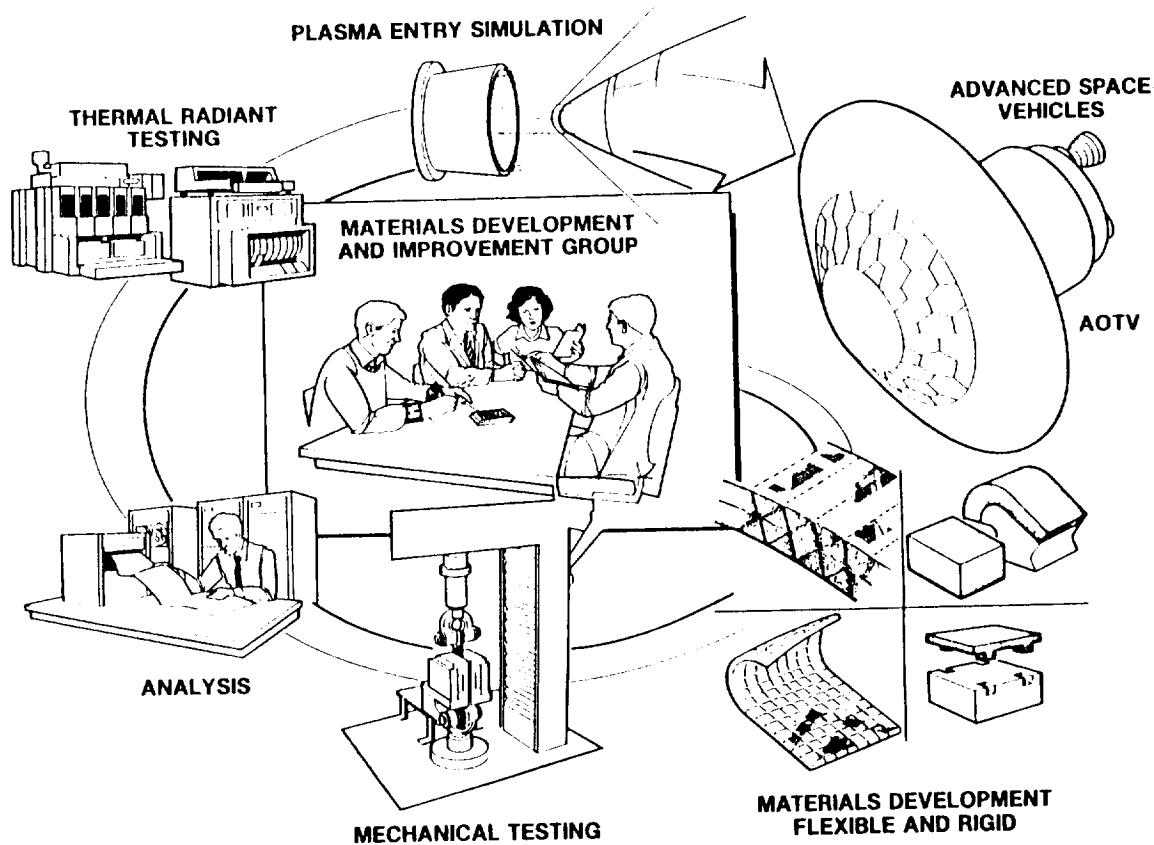
Three types of passive thermal protection systems have been developed over the not very long history of supersonic/hypersonic flight. These include heat sinks which store the incoming heat, ablative thermal protection systems which dissipate the heat by decomposing and reradiating it to the environment, and insulative systems which reradiate nearly all the heat to the environment. In the early days of hypersonic flight the first two thermal protection schemes were used most of the time because they were self regulating, could be designed with a large margin of safety to compensate for the unknowns in the entry heating environment and were capable of surviving the high heat fluxes experienced by ballistic reentry vehicles. Most used ablative thermal protection including Apollo, Gemini, Viking and virtually all ballistic missiles. A few, such as PAET, used heat sink. In the sixties research on reusable manned high L/D reentry vehicles was initiated. Many potential reusable thermal protection systems were studied. It was found that for manned reentry vehicles which experienced mild heating environments, a passive insulation system was the most weight efficient and generally the safest. Active thermal protection concepts, which are used in propulsion systems and have been studied extensively for manned reentry vehicles, are discussed by others in this workshop.

Passive insulation systems can be divided into two groups: the load carrying hot structure type of TPS, such as carbon/carbon, which requires an insulator under it to protect the cold structure, and the surface insulation type which is nonload carrying but transmits the aerodynamic loads to the structure through a strain isolator and is itself the thermal protection system. Both metallic and ceramic insulations have been studied. In this paper I will discuss the ceramic Reusable Surface Insulation (RSI), which is the type primarily being used today. RSI absorbs the incoming radiative or convective heat at its surface

and then reradiates most of it to the environment while conducting the smallest amount possible (usually less than 3%) to the structure. The RSI heat shielding concept was originally developed by Lockheed Missiles and Space Company in the early 1960s and was adopted by NASA for the Space Shuttle Orbiter in the early 1970s. The original heat shield material adopted for the Space Shuttle in 1973 was LI-900. Families of rigid and flexible external insulations have subsequently been developed over the last twenty years. This paper will discuss the evolution, characteristics, and state of the art of RSI with particular emphasis on the materials and systems developed by NASA-Ames Research Center.

## THERMAL PROTECTION SYSTEM DEVELOPMENT PROCESS

This chart illustrates the closed loop development process at Ames where thermal protection materials are processed from raw materials inhouse, and tested mechanically, chemically, thermally and then can be evaluated under reentry conditions in our arc jet facilities. Materials supplied by industry and other government laboratories can be and are integrated into this process at any point in their development. The products of this development procedure are often materials including manufacturing specifications that can be adopted by industry and the test data required for certification.



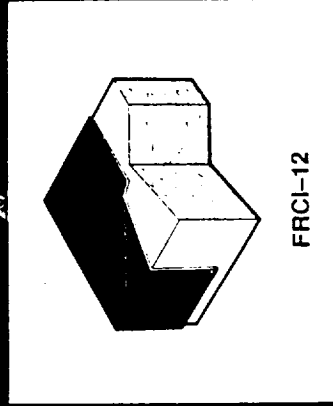
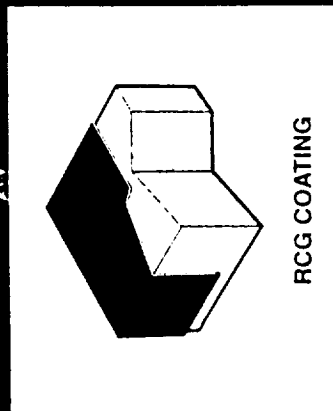
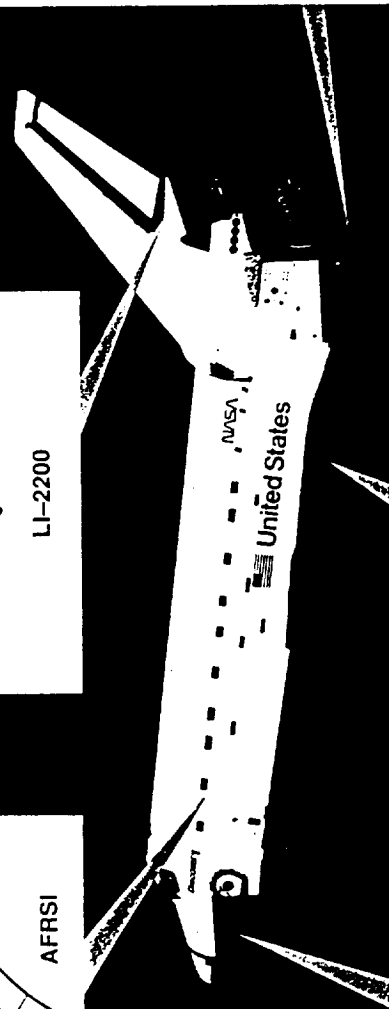
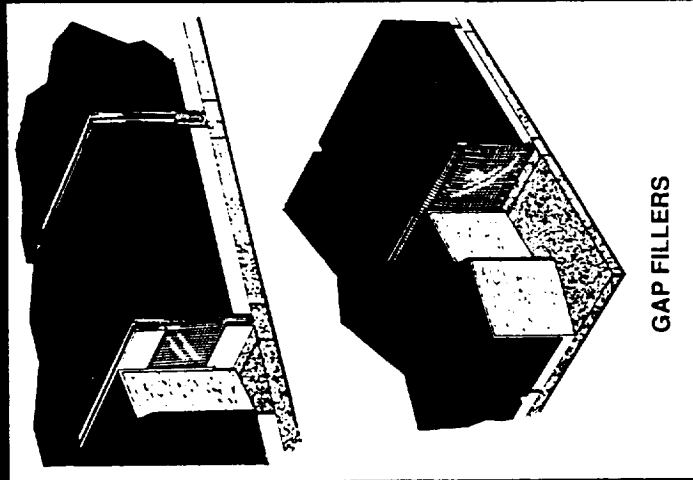
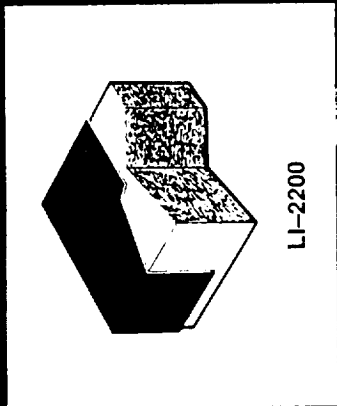
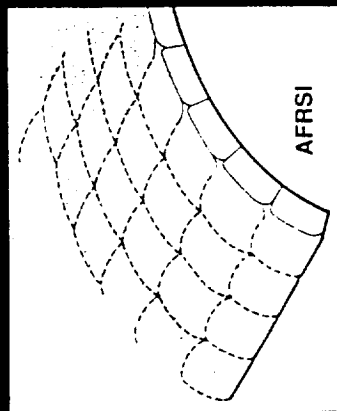
## EXAMPLES OF SHUTTLE RSI DEVELOPMENT CHALLENGES

Among the most challenging aspects of Space Shuttle Orbiter design and manufacturing were the development of the new reusable surface insulations. Not only did the materials start as laboratory curiosities but even the raw materials had to be upgraded and in some cases new processes developed to meet the shuttle requirements. The purity of the silica fibers manufactured by Johns Manville were improved substantially to meet the requirement that RSI tiles had to be reusable for 100 flights. A new manufacturing process developed for the modified Vycor glass used in the tile coating is now used by Corning Glass Works. Several new tile and coating materials were developed including The Reaction Cured Glass Coating, LI2200, Fibrous Refractory Composite Insulation etc. and are now manufactured by LMSC, Rockwell and others.

Among the other difficult problems in development of the thermal protection system were designing and manufacturing it so that the TPS was durable and properly strain isolated from the structure. Meeting the smoothness and tile gap requirements were great challenges. The system finally developed is deceptively simple in appearance, but reflects an extraordinary accomplishment by the NASA/industrial team.

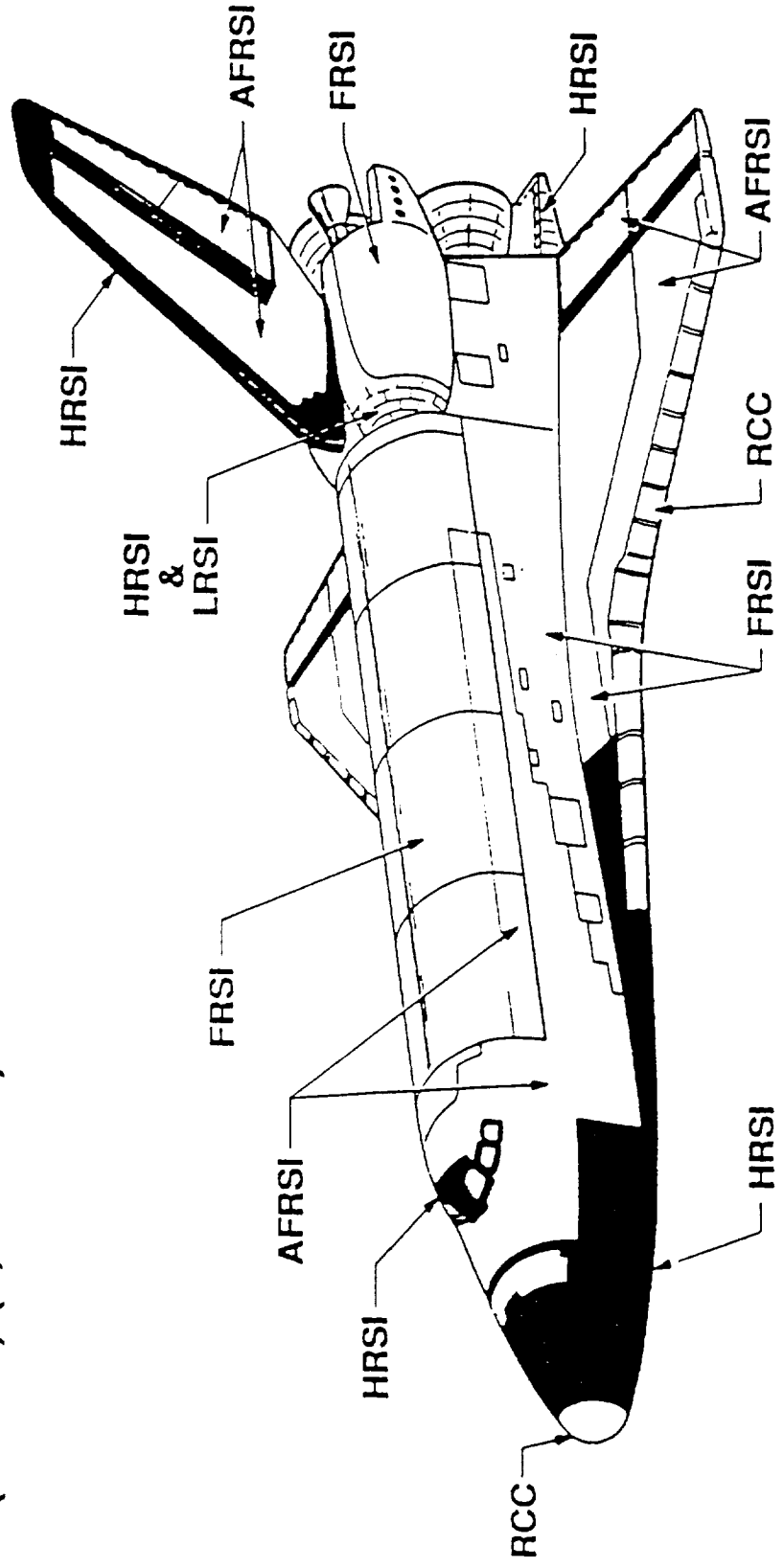
- MANUFACTURING
  - RAW MATERIALS: FIBERS, COATING COMPONENTS
  - PROCESSES: SLURRY BLENDING, PRODUCTION UNIT MOLDING, SINTERING, TILE MACHINING, GLAZING
- DESIGN
  - TILE PLANFORM SIZE
  - STRAIN ISOLATION
  - GAP HEATING
- INSTALLATION
  - BONDING, BOND VERIFICATION
  - TOLERANCES
  - QUALITY CONTROL
- OPERATION
  - DURABILITY
  - WATERPROOFING

# AMES DEVELOPED THERMAL PROTECTION MATERIALS



## SHUTTLE ORBITERS TPS LOCATIONS

TOTAL RSI CERAMIC TILES - 24,300  
REINFORCED CARBON/CARBON (RCC) (44 PANELS/NOSE CAP)  
FELT REUSABLE SURFACE INSULATION (FRSI) (3,581 FT<sup>2</sup>)  
ADVANCED FLEXIBLE REUSABLE SURFACE INSULATION  
(AFRSI) (4,100 FT<sup>2</sup>)



## **LESSONS LEARNED**

There is a tendency to be overly optimistic in the beginning of a development program. Even when a new system being developed is intentionally simple such as the RSI, unexpected problems will occur. The design requirements must be carefully defined and adequate testing done early so that problems are caught before the commitment to manufacturing becomes too costly to modify. Details such as the adequacy of the tile bonding specifications and quality control cannot be ignored. End to end system testing must be done early.

- **MURPHY'S LAW ALWAYS APPLIES TO NEW MATERIALS**
- **BE SURE DESIGN REQUIREMENTS ARE NECESSARY AND REALISTIC**
- **TEST PROGRAMS MUST BE ADEQUATE AND EARLY**
- **CANNOT IGNORE DETAILS**

## **NEW THERMAL PROTECTION TECHNOLOGY DIRECTED TOWARDS:**

- **SAVING WEIGHT**
- **LOWERING COST**
- **INCREASED TEMPERATURE CAPABILITY**
- **INCREASED DURABILITY**
- **IMPROVED RELIABILITY**

### **THERMAL PROTECTION MATERIALS AND STRUCTURES TECHNICAL DEVELOPMENT PRIORITIES**

- **VERY-HIGH TEMPERATURE, REUSABLE MATERIAL (4000F+)**
  - zirconium and hafnium based ceramics (diborides and zirconia development)
- **HIGH TEMPERATURE, HIGH STRENGTH TO WEIGHT MATERIALS**
  - ceramic matrix composites (sic/sic, c/sic, etc)
- **LIGHT WEIGHT REUSABLE SURFACE INSULATIONS**
  - flexible (TABI, CFBI) and rigid (TUFI, FRCI, AETB, ASMI)
- **HIGH EMITTANCE, LOW CATALYTIC EFFICIENCY COATINGS**
  - coating development/evaluations
- **NEW LEADING EDGE, NOSE TIP AND THERMAL PROTECTION CONCEPTS**
  - small radius non ablating leading edges and nose caps
  - spinning leading edge
  - Pegasus wing glove

**NASA Ames-Thermal Protection Materials Branch**



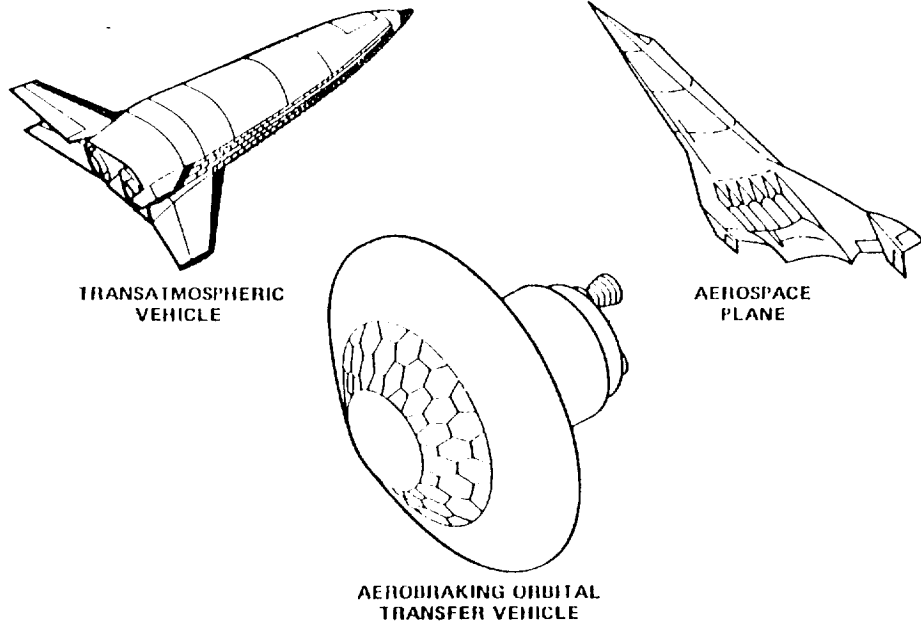
## **PRIORITY RATIONALE**

- **VERY-HIGH TEMPERATURE MATERIALS (4000F+) REPRESENT A POTENTIAL BREAK THROUGH IN THE DEVELOPMENT OF ADVANCED HEAT SHIELDS (2 TO 5 TIMES HEAT FLUX CAPABILITY OF CC OR SIC)**
- **SIC/SIC AND C/SIC CERAMICS(HIGH TEMPERATURE/HIGH STRENGTH TO WEIGHT MATERIALS) HAVE POTENTIAL FOR GREATER CAPABILITY AND DURABILITY THAN CC**
- ADVANCED LIGHT WEIGHT REUSABLE EXTERNAL INSULATIONS, THE "WORK HORSE" OF THERMAL PROTECTION MATERIALS, ARE IN CONTINUING DEMAND BY INDUSTRY, NASA AND DOD**
- IMPROVED HIGH EMITTANCE, LOW CATALYTIC EFFICIENCY COATINGS WILL HAVE A LARGE IMPACT ON THE PERFORMANCE OF THERMAL PROTECTION SYSTEMS**
- ALL THESE MATERIAL RESEARCH AREAS ARE CRITICAL TO THE DEVELOPMENT OF HYPERSONIC CRUISE AND SPACE EXPLORATION VEHICLES**
- APPLICATION OF THESE MATERIALS TO REALISTIC STRUCTURES AND VEHICLES (LEADING EDGES, NOSETIP AND THERMAL PROTECTION CONCEPTS) IS CRITICAL TO THEIR DEVELOPMENT AND EVENTUAL USE**

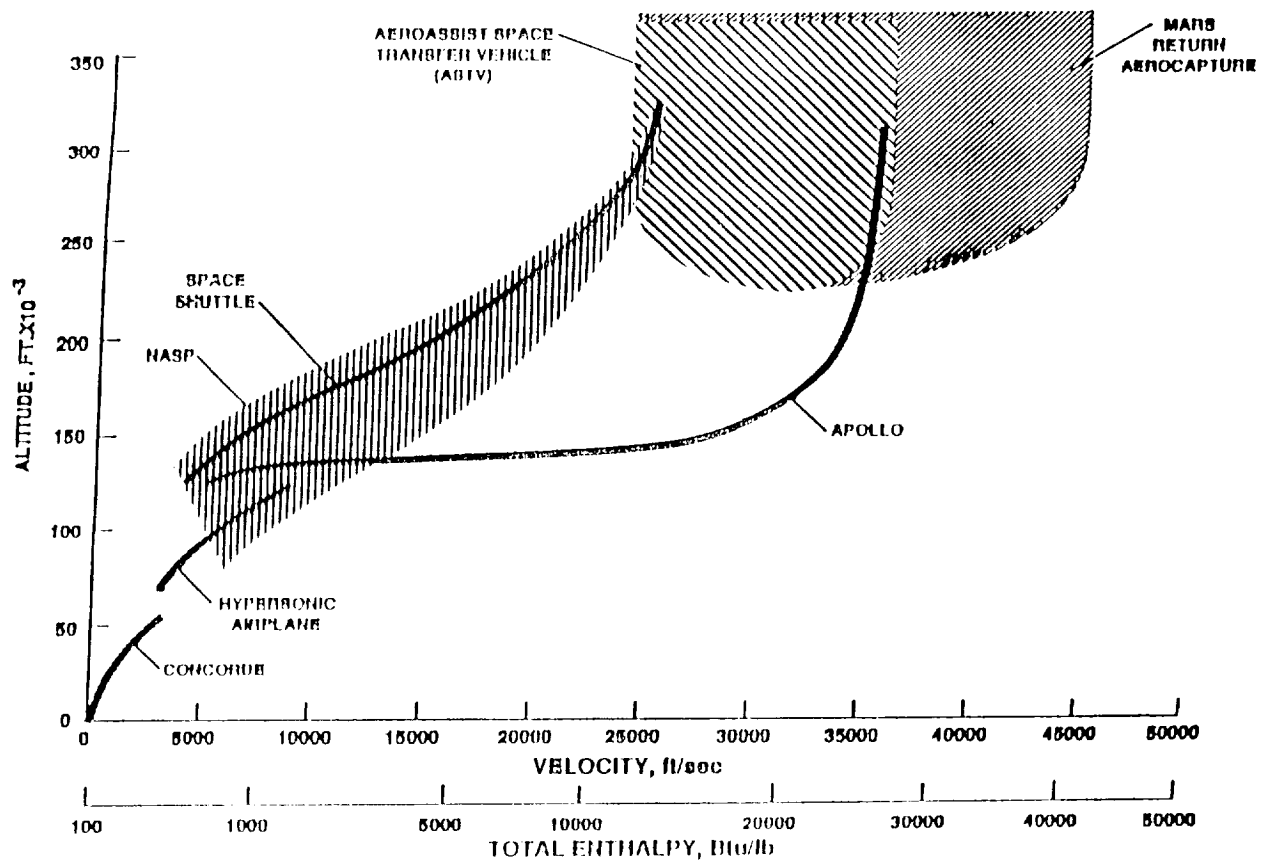
## **FUTURE MISSIONS**

- **SPACE SHUTTLE UPGRADE**
- **NEXT GENERATION SPACE TRANSPORTATION SYSTEM**
  - NATIONAL AEROSPACE PLANE
  - SHUTTLE EVOLUTION-II/C
  - NATIONAL LAUNCH SYSTEM (ADVANCED LAUNCH SYSTEM)
  - ASSURED CREW RETURN VEHICLE FOR SPACE STATION (PERSONAL LAUNCH SYSTEM)
- **SPACE EXPLORATION**
  - MARS SAMPLE RETURN
  - LUNAR RETURN AEROBRAKES
  - MANNED MARS AEROBRAKE AND RETURN.
  - PLANETARY PROBES: NEPTUNE, TITAN, VENUS, URANUS
- **FLIGHT EXPERIMENTS**
  - AEROASSIST FLIGHT EXPERIMENT, ??
  - SWERVE-PEGASUS

## ADVANCED SPACE VEHICLES



## COMPARISON OF VEHICLE REGIMES IN EARTH'S ATMOSPHERE



# SEI/PATHFINDER

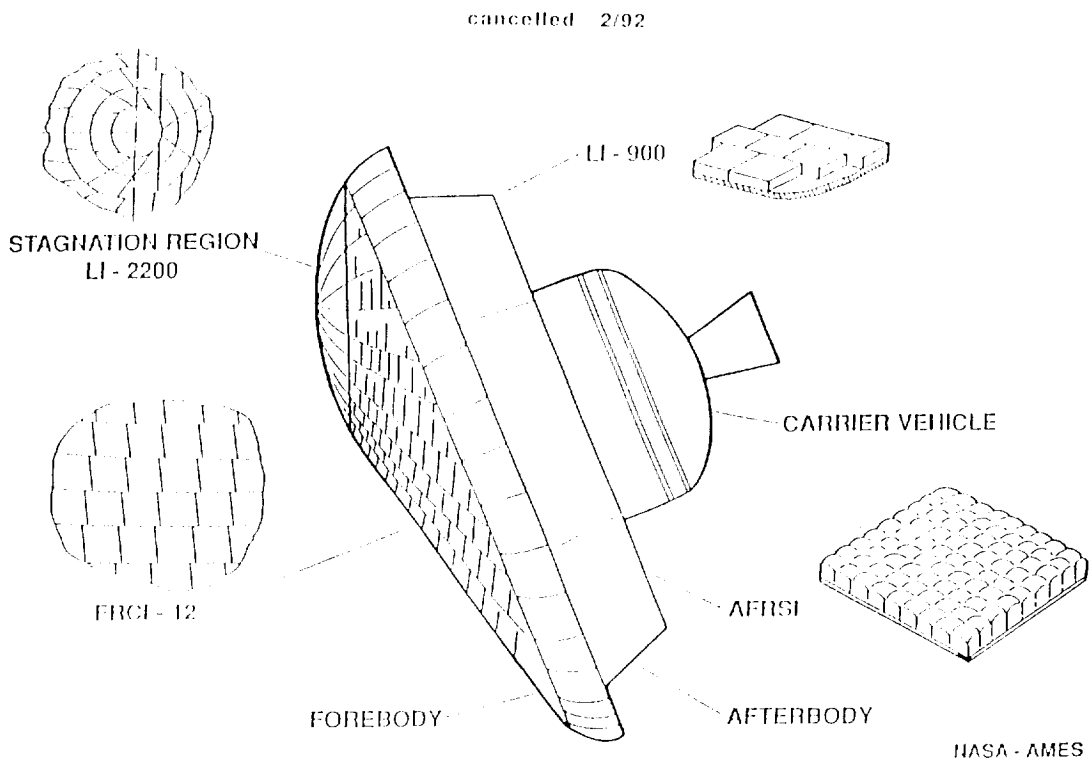
## COMPARISON OF ASTV AND SHUTTLE TPS REQUIREMENTS

	SHUTTLE	LUNAR RETURN ASTV	MARS RETURN ASTV
• PEAK CONVECTIVE HEATING BTU/FI <sup>2</sup> -SEC	60	3-60	50-1500
• PEAK VELOCITY, MI/SEC	4	7+	11+
• PEAK RADIANT HEATING, BTU/FI <sup>2</sup> -SEC	< 2	3 - 30	25-800
• PEAK DYNAMIC PRESSURE, PSF	200	< 30	< 30
• TURBULENT HEATING	YES	NO	YES
• ENTRY HEATING TIME, SEC	1200	< 400	< 400
• EXPOSURE TO ADVERSE ENVIRONMENTS			
- HANDLING	YES	NO*	NO*
- RAIN/WEATHER	YES	NO	NO*
- AEROACOUSTICS (dB)	160+	< 90	< 90
- DEBRIS IMPACT			
- LAUNCH	YES	NO	NO
- ON ORBIT/IN FLIGHT	LESS	MORE	MORE

\*ONCE DEPLOYED

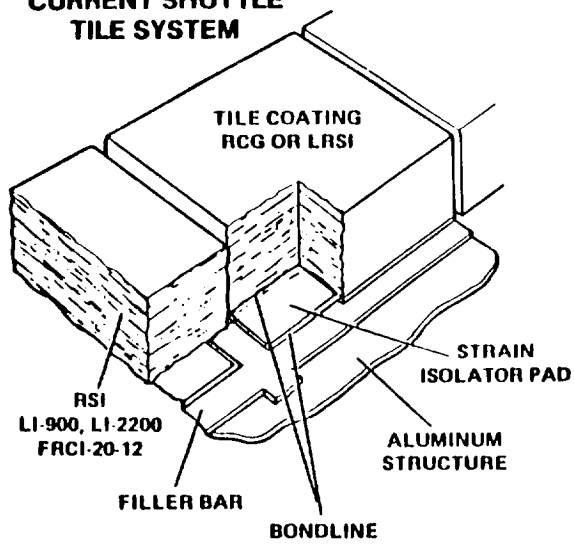
## THERMAL PROTECTION SYSTEM DESIGN FOR AEROASSIST FLIGHT EXPERIMENT (AFE)

The Aeroassist Flight Experiment (AFE) was funded and developed in the late 1980s. Flight was to occur about 1996. This figure illustrates the thermal protection system design. The aerobrake was designed and built by JSC. Shuttle state of the art RSI tiles and blankets used were manufactured by Lockheed Missiles and Space Company and Johns Manville. Lessons learned on the shuttle were taken into account, resulting in a thermally efficient, very cost effective design and trouble free manufacturing process. Advanced RSI tiles and Flexible insulations shown in the following charts were to be flown as experiments. Unfortunately, AFE was cancelled in early 1992.

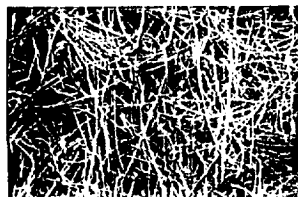
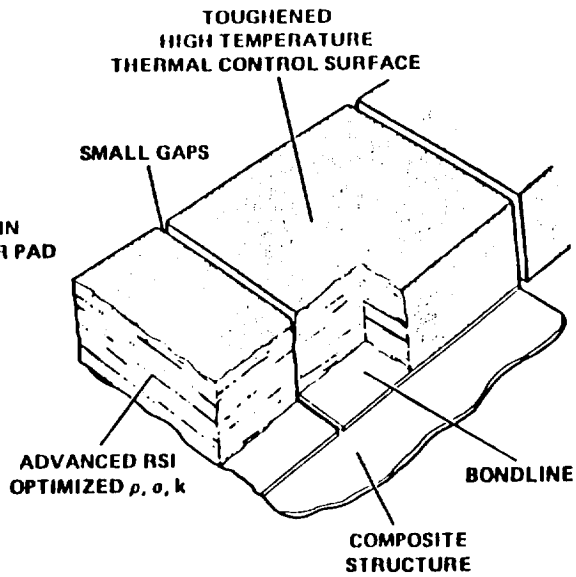


## ADVANCED RSI THERMAL PROTECTION SYSTEMS

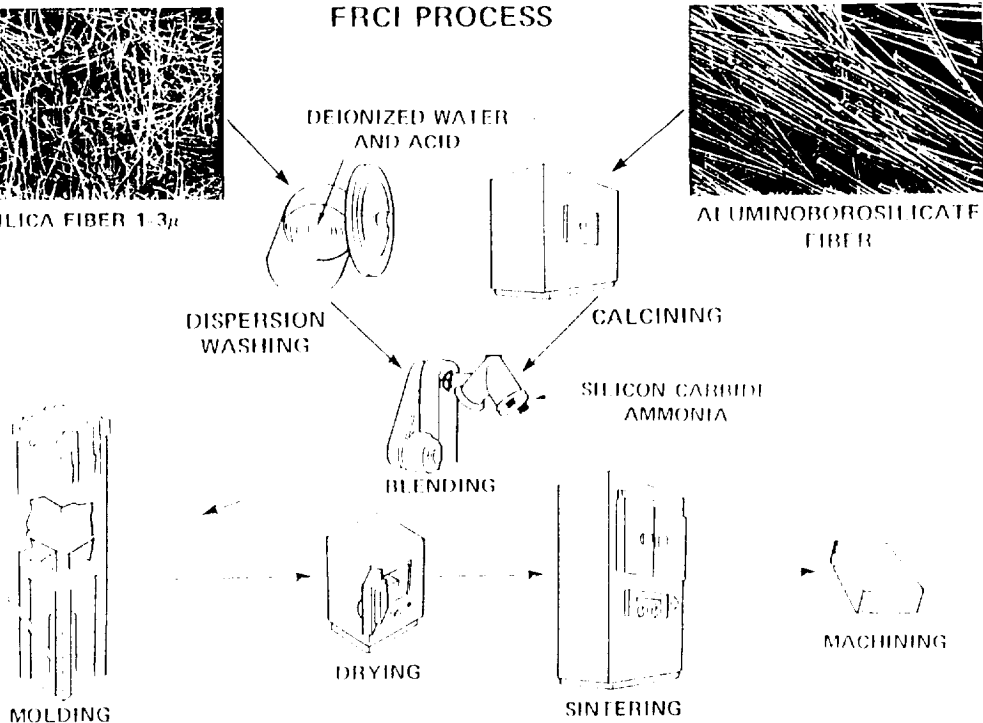
### CURRENT SHUTTLE TILE SYSTEM



### ADVANCED TILE SYSTEM

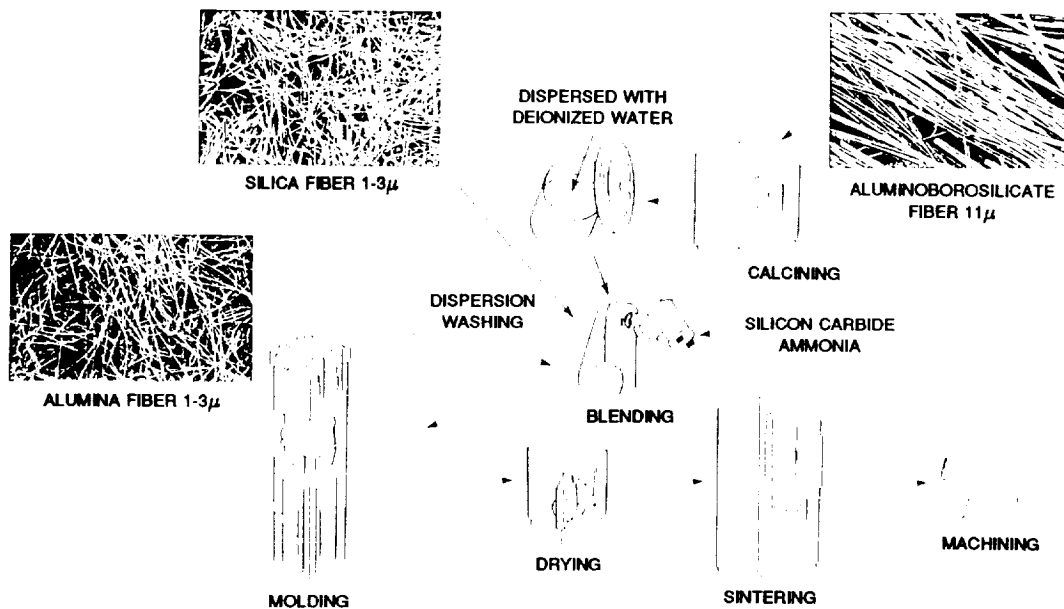


### FRCI PROCESS



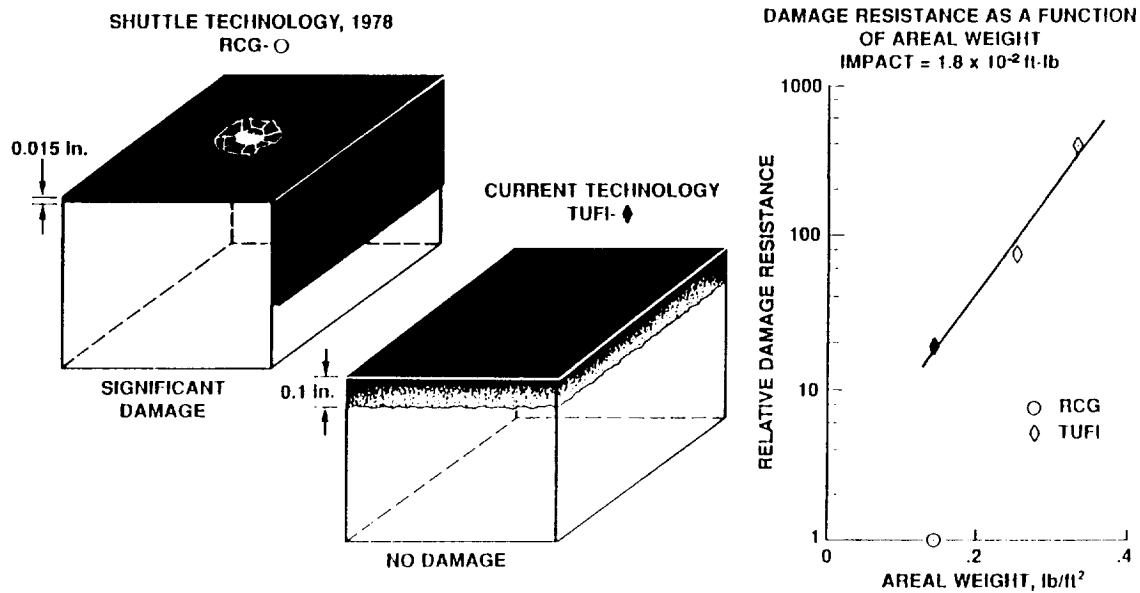
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## AETB PROCESS



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## IMPACT RESISTANCE OF RSI COATING SYSTEMS

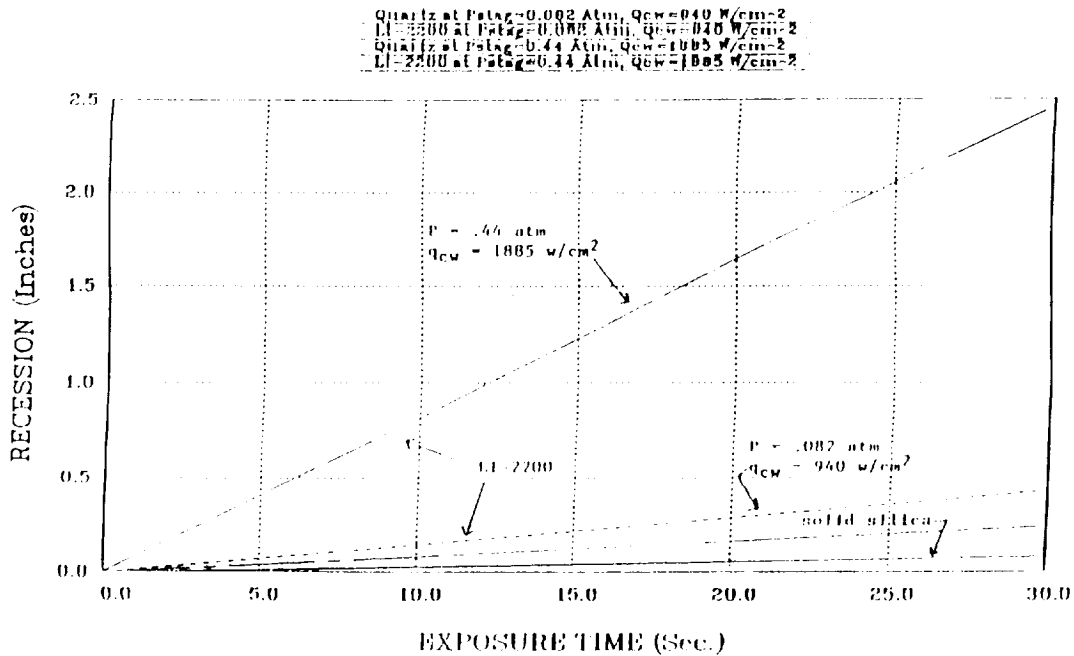


# RIGID RSI PROPERTY COMPARISON

PROPERTIES	RIGID RSI MATERIALS				
	LI-900	LI-2200	FRCI-12	AETB-12	FRCI-12-20*
DENSITY, LB/FT <sup>3</sup>	9	22	12	12	20
TENSILE STRENGTH					
IP (PSI)	68	184	256	157	630
III (PSI)	24	23	81	120	230
MODULUS					
IP (KSI)	25	80	50	32	110
III (KSI)	7	27	10	16	46
TEMPERATURE CAPABILITY (ISOTHERMAL SHRINK)					
2700°F - IIR (%)	91		77	42	67
2500°F - IIR (%)	53	37	44	12	38
THERMAL CONDUCTIVITY PRESSURE = 10 <sup>-3</sup> ATM, T = 1000°F BTU-IN/FT <sup>2</sup> -HR°F	0.021	0.030	0.027	0.024	
YEAR DEVELOPED	1973	1977	1980	1985	1991

\*15% AMORPHOUS

## RECESSION DATA FOR ABLATION OF LI-2200 (RSI) COMPARED TO SOLID QUARTZ (AMES 60 MW Arc-Jet)



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**MANNED MARS/EARTH RETURN  
THERMAL PROTECTION ABLATOR MATERIALS COMPARISON\***  
(RAKED CONE GEOMETRY)  $R_N = 1$  METER

$$V_E = 14 \text{ km/sec}, L/D = 0.5, \beta = 300 \text{ kg/m}^2$$

	CARBON <sup>1</sup> PHENOLIC	AVCOAT <sup>2</sup>	RSI (LI-2200) <sup>3</sup>	AVCOAT (APOLLO) <sup>†</sup>
ABLATOR THICKNESS (IN)	1.1	1.75	2.75	0.5 - 2.5
INSULATION ** THICKNESS (IN)	2.0	1.0	1.0	(---)††
AVERAGE MASS LOADING (lbm/ft <sup>2</sup> )	9.66	5.71	5.79	1.5 - 7.0
TPS MASS	3478	2056	2084	1635
TPS WT. %	23.2%	13.7%	13.8%	13.2%

\* FOREBODY HEATSHIELD ONLY; BASED ON NON-OPTIMIZED DESIGN, I.E. UNIFORM THICKNESS; DOES NOT INCLUDE TPS SUPPORT STRUCTURE

\*\* LI-900 RSI INSULATION

† APOLLO ENTRY VELOCITY,  $V_E = 11 \text{ km/sec}$ ,  $R_N = 1.0 \text{ ft}$ ,  $\beta = 350 \text{ kg/m}^2$

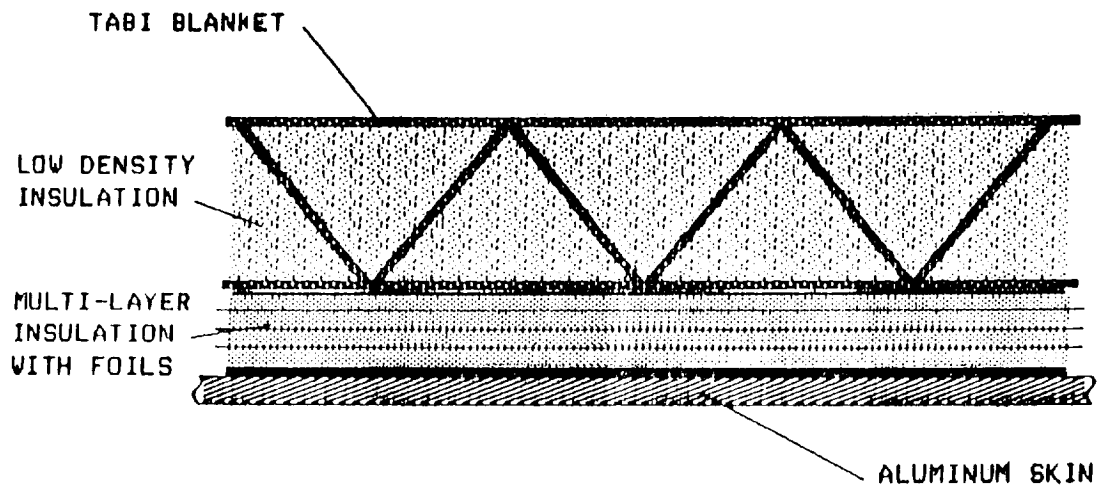
†† APOLLO INSULATION IS Q-FELT/STAINLESS STEEL HONEYCOMB (Q-FELT INCLUDED IN TPS MASS)

<sup>1</sup> INITIAL DENSITY,  $\rho_o = 89 \text{ lb/ft}^3$

<sup>2</sup> INITIAL DENSITY  $\rho_o = 34 \text{ lbm/ft}^3$

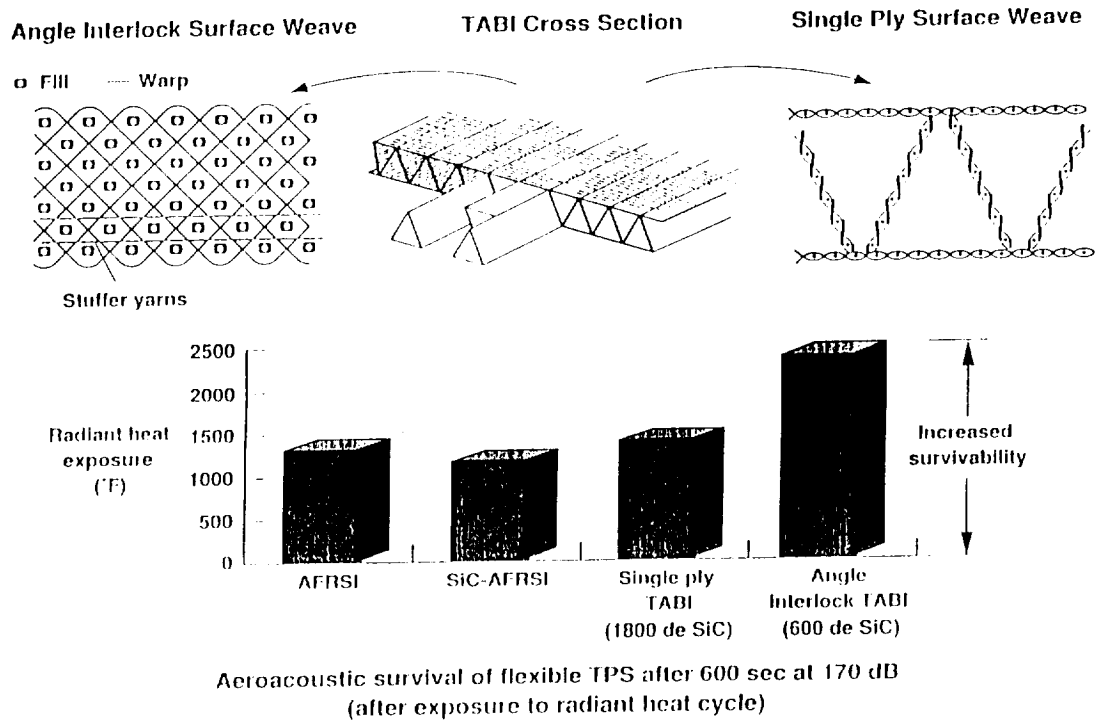
<sup>3</sup> INITIAL DENSITY,  $\rho_o = 22 \text{ lbm/ft}^3$

## FLEXIBLE TPS CONSTRUCTION

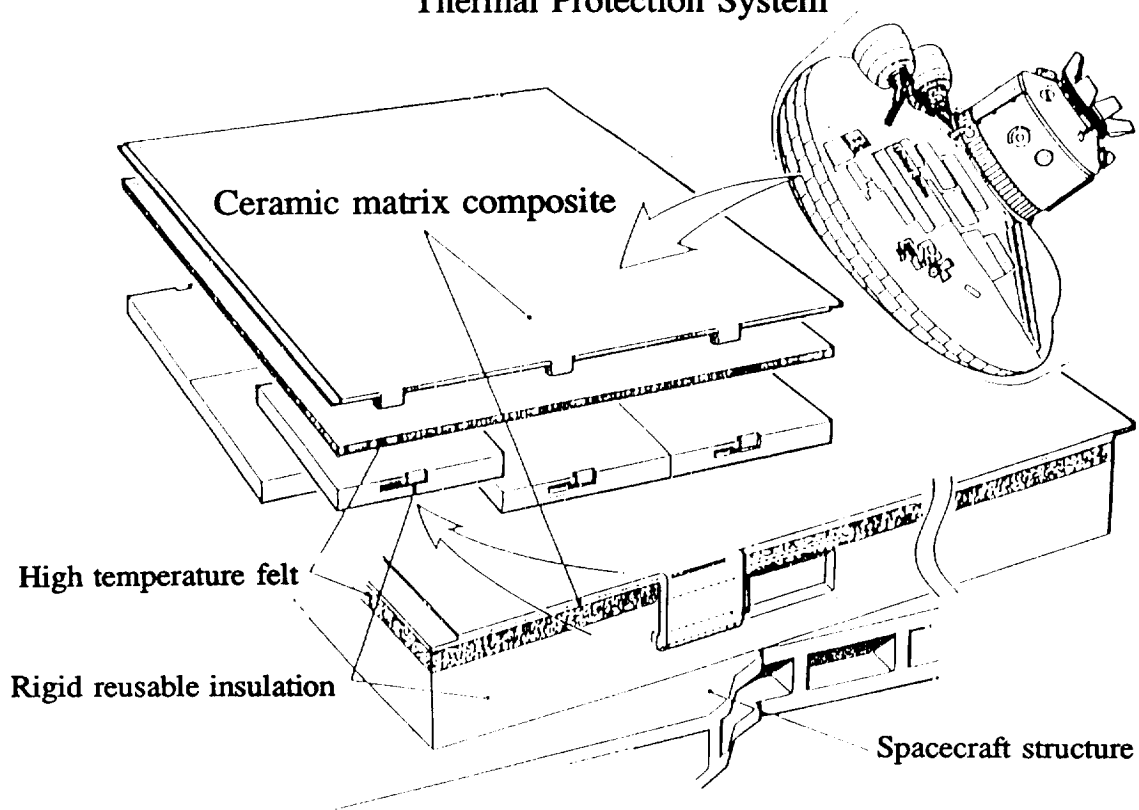




## SURFACE TOUGHENING OF TABI TO AEROACOUSTIC ENVIRONMENTS



## TOP HAT Thermal Protection System



## CURRENT HEAT SHIELD MATERIALS THERMAL LIMITS

MATERIAL	MAXIMUM USE TEMPERATURE, °F		EMITTANCE (@ °F)	MAXIMUM HEAT FLUX CAPABILITY* BTU/FT <sup>2</sup> -SEC	EQUIVALENT USE TEMPERATURE, °F***
	MULTIPLE FLIGHT	SINGLE FLIGHT			
FLEXIBLE ORGANIC					
FRSI	700	800	.9(800)	1.4	885
PBI	900+	1100	.9(1100)	2.7	1125
AFRSI, TABI, CFBI					
SILICA	1200	2000	.43(2000)	4.4	1480
NEXTEL	> 2000	> 2000	.48(2000)	> 7.5	1820
NICALON	2000	> 2400	.58(2000)	> 30	
RIGID CERAMIC INSULATION					
LI-900	2500	2700	.9(2500)	60	2980
LI-2200	2600	2800			
		(2900 FOR AFE)		(80)	
FRCI-12	2600	2800	.9(2500)	70	3115
AETB-12/IUFI	2500	2700**		60	
AETB-12/RCG	2600+**	2800+**		70	
ASMI	2600+**	2900**		80	
AETB-8/RCG	2600**	2800+**		70	
METAL			.8		
TITANIUM	1000			1.7	1000
RENE 41	1600			6.9	1600
INCONEL 617	2000			14	2000
RCC/ACC			.8		
	3000			55 (F.C.)	3000
				100 N.C.	3560

## THERMAL PROTECTION TECHNOLOGY FOR HYPERSONIC VEHICLES

### STATUS OF DEVELOPMENT

- RIGID LOW DENSITY CERAMIC
  - SHUTTLE TPS FLIGHT PROVEN
    - LI-900, LI-2200, FRCI-20-12
  - IMPROVED MATERIALS DEVELOPED
    - FRCI, AETB, HIP
    - TOUGHENED COATING
  - OPTIMIZED MATERIALS TO BE DEFINED
- RIGID HIGH DENSITY CERAMIC
  - SHUTTLE CARBON/CARBON TPS FLIGHT PROVEN
  - CERAMIC MATRIX COMPOSITES IN DEVELOPMENT
  - DIBORIDE COMPOSITES RESEARCH INITIATED
- FLEXIBLE
  - SHUTTLE TPS FLIGHT PROVEN FRSI, AFRSI
  - IMPROVED MATERIALS UNDER DEVELOPMENT TABI, CFBI, MLI CERAMIC COMPOSITS
- ABLATORS
  - APOLLO, MERCURY, GEMINI LOW DENSITY TPS FLIGHT PROVEN
    - AVCOAT 5026, SLA 561, etc.
  - BALLISTIC MISSILE, GALILEO HIGH HEAT FLUX TPS FLIGHT PROVEN
    - CARBON/PHENOLIC, CARBON/CARBON
  - NON CATALYTIC REFLECTIVE INSULATIVE ABLATORS DEVELOPMENT STARTING